High Energy perspectives for the study of the Galactic Center

A. Goldwurm
With contributions/material from
R. Terrier, M. Clavel, G. Ponti, S. Soldi

Workshop :
The Future of Hard X-ray Astrophysics (1-500 keV): Science and Instrument Prospects

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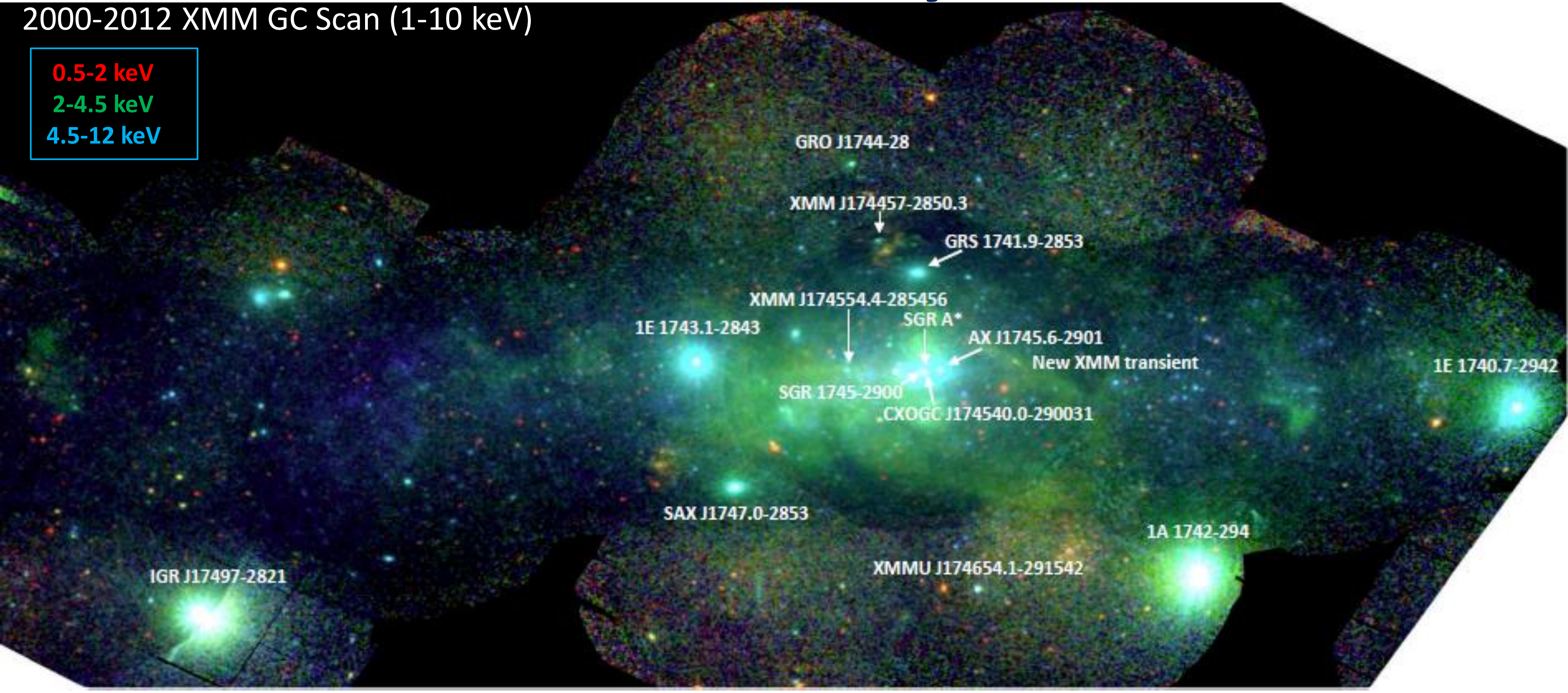
Plan

- **The GC as a AHE laboratory, overview**
- **Sgr A***
  - **Quiescent emission**
  - **Flaring emission**
- **Sgr A* Past and Future activity**
- **Non-thermal features and the hard component of the diffuse emission**
- Soft component/warm plasma: outflows
- Cosmic rays, TeV emission, 511 keV line em.

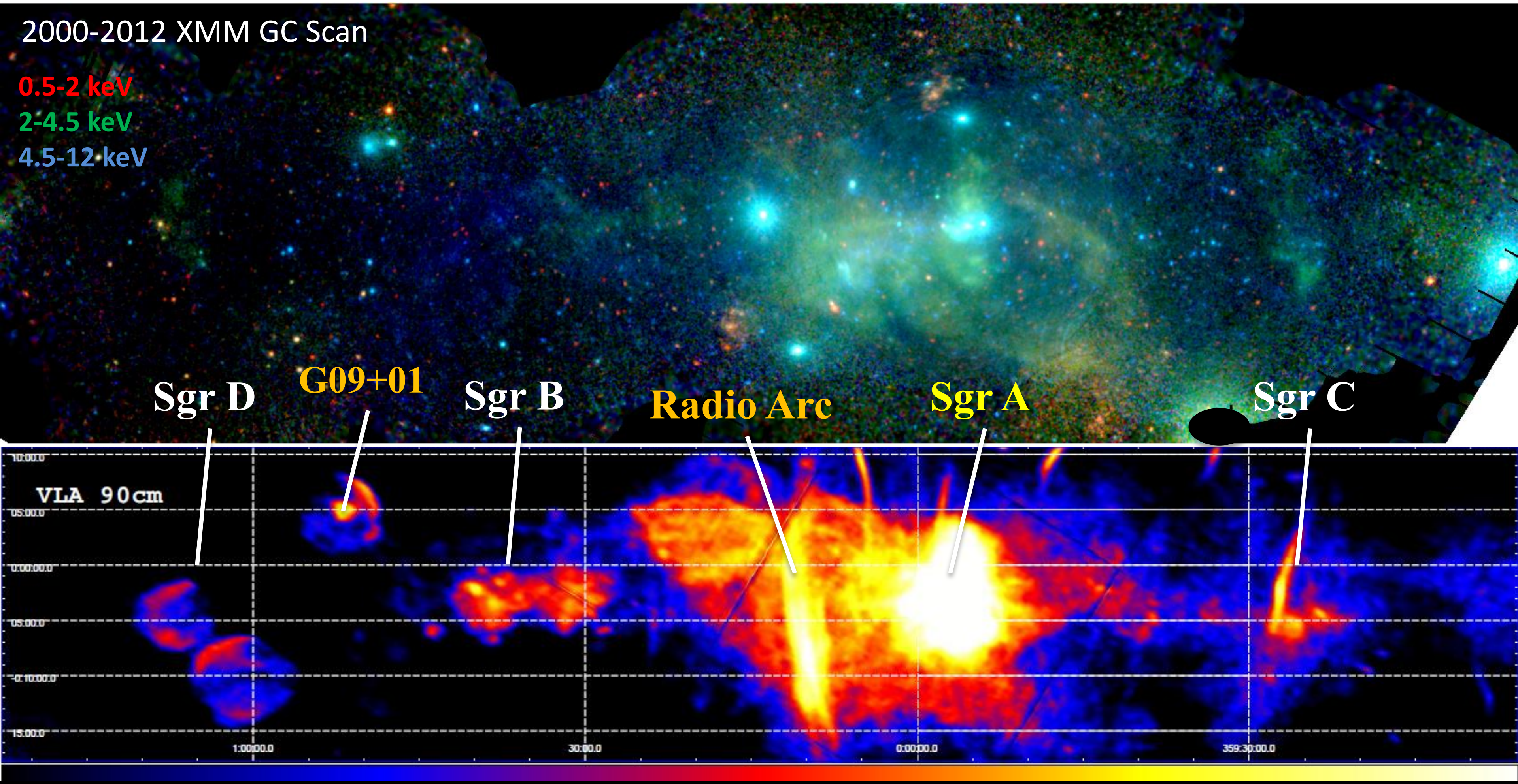
The GC High Energy Astrophysics laboratory



- Galactic Center region: the inner 2°x 1°~ 300 pc × 150 pc (Central Molecular Zone)
- X-Ray images of GC dominated by XRBs (the whole variety)
- Many other point and diffuse sources: a very complex and active region
- Several Diffuse components: Soft Thermal, Hard Th + Fe 6.7, Non-Th + Fe 6.4

(PI of 2012 XMM scan R. Terrier, Ponti et al 14, Soldi et al 14 in prep, ..)

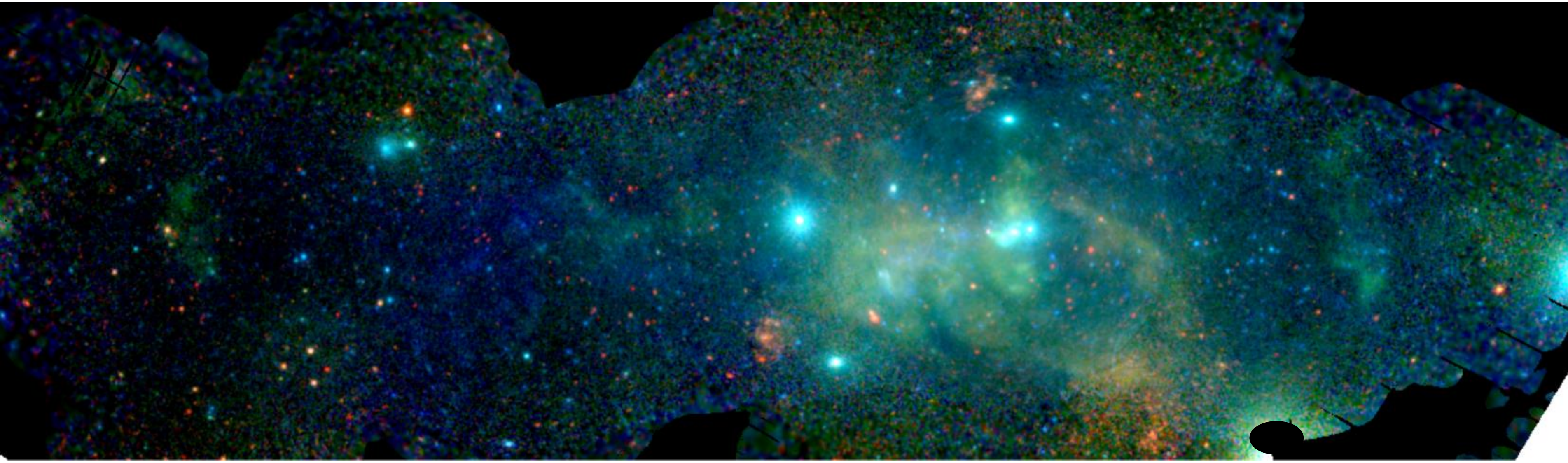
GC: X vs Radio

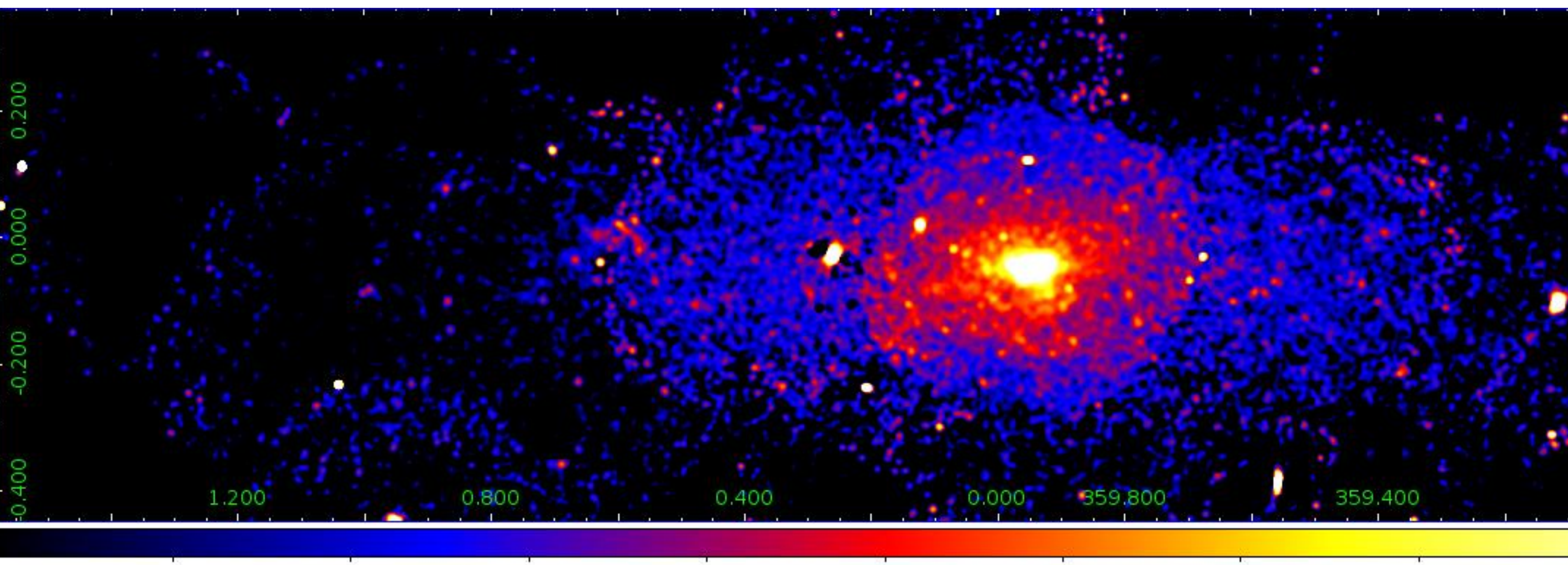


Radio:

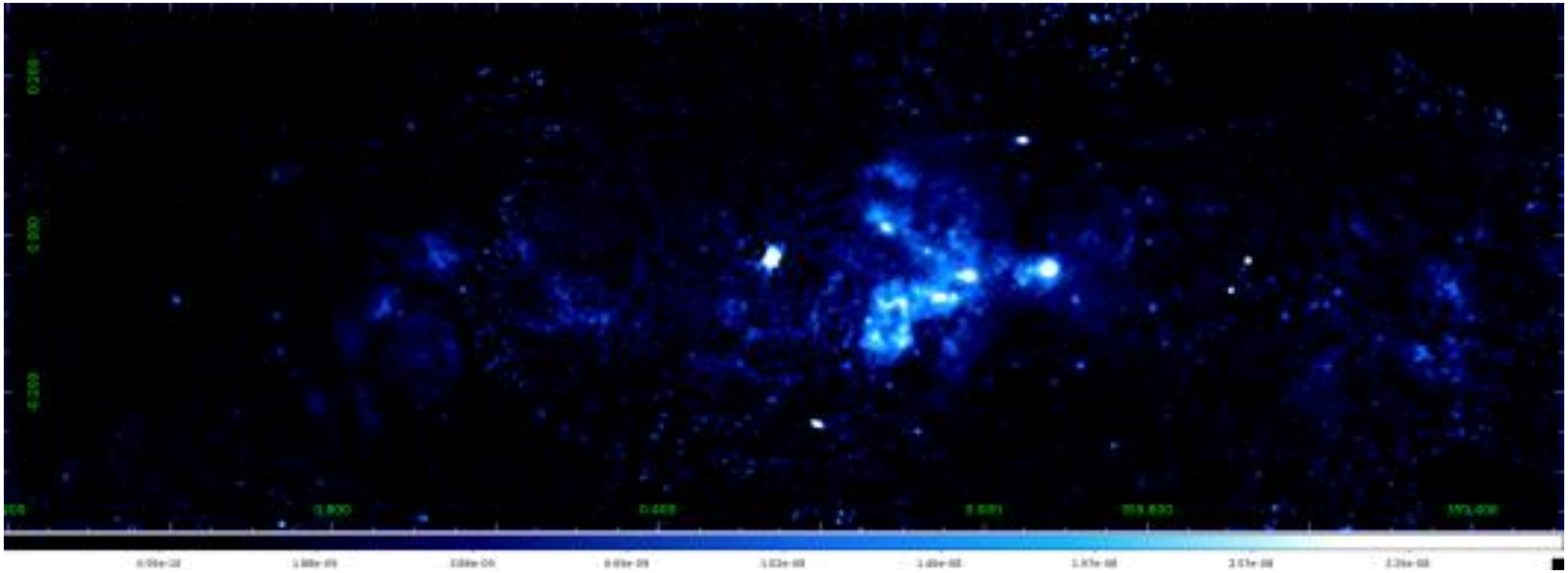
- Thermal emis. dense/massive Molecular Clouds correlated to X-ray 6.4 keV line
- Non-thermal filaments and SuperNova Remnants
- The bright central Sgr A complex includes several objects (Sgr A E, CND, Sgr A W)

Emission of the ionized Fe K_α line at 6.7 keV



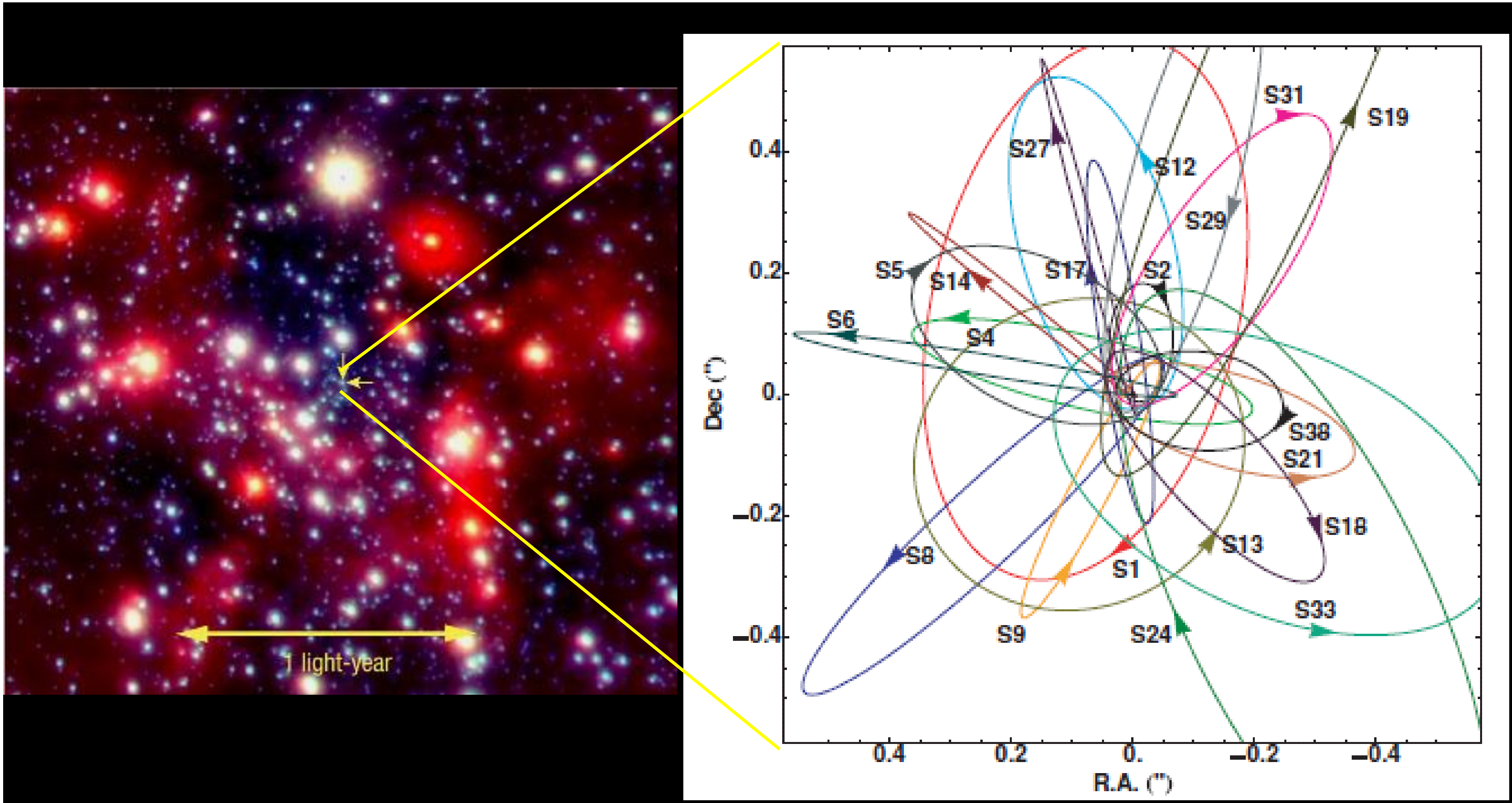


Emission of neutral Fe K_α line at 6.4 keV



(PI of 2012 XMM scan R. Terrier, Ponti et al 14 in prep, Soldi et al 14 in prep, ..)

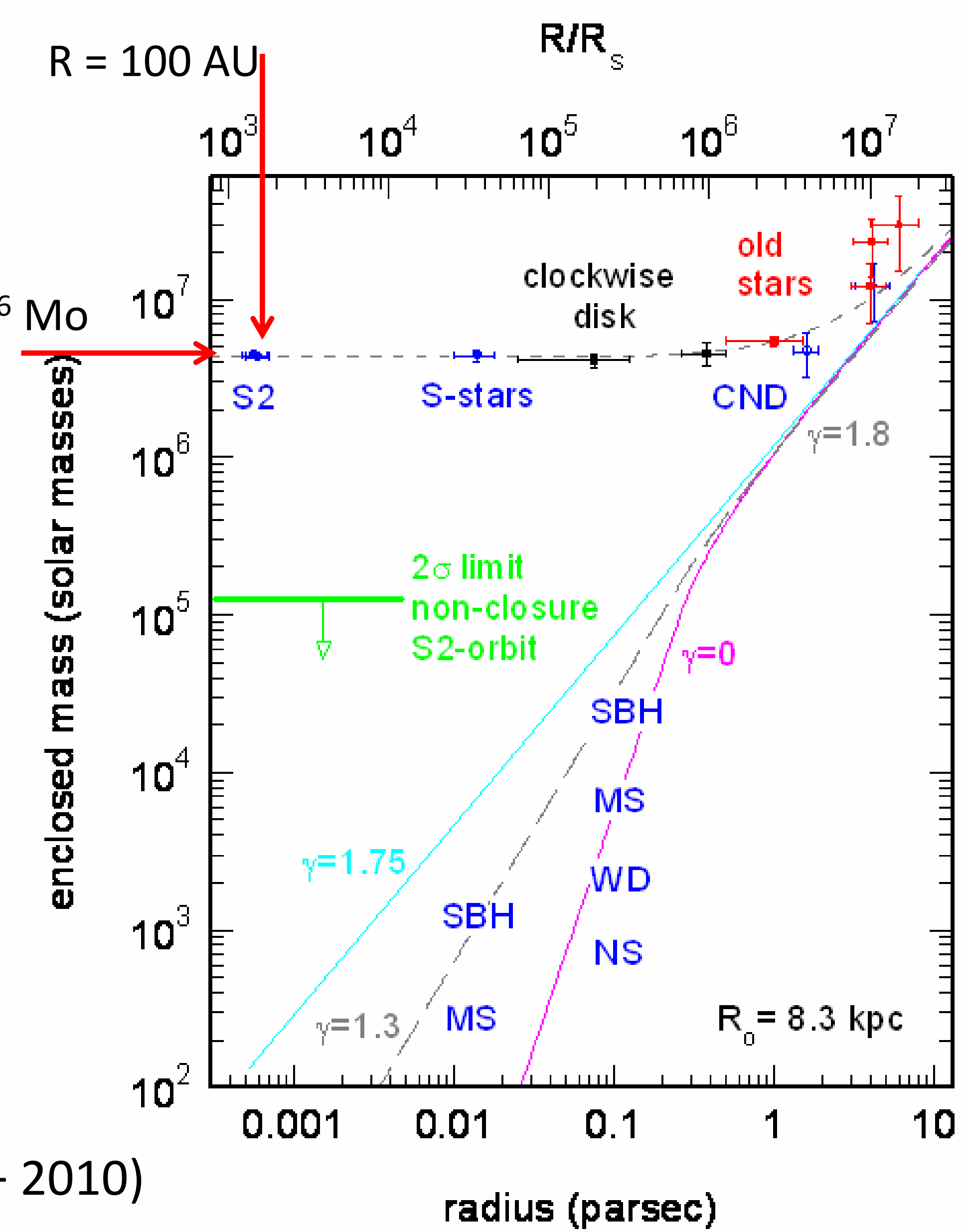
The GC SuperMassive Black Hole



- NIR measurements with VLT and Keck Obs. of proper motions of the central cluster (< 0.1 pc) stars provide orbital parameters of tens of stars => mass of the gravitational potential
- **Enclosed Dark Mass ≈ 4 10^6 $M_\odot$ within** ~ 45 **AU (≈ 570 R_S)**

⇒ **SUPER-MASSIVE BLACK HOLE** (Genzel etal '03, Ghez etal '05 08, Gillessen etal 09)

The GC SuperMassive Black Hole



(Genzel+ 2010)

Measurements imply

$M = 4\ 10^6\ M_\odot$ dark material

$R < 100$ AU

$\Rightarrow$ S-M Black Hole

$M_\bullet = 4\ 10^6\ M_\odot$

$R_S = 1.2\ 10^{12}$ cm = 1/10 AU

$L_E = 5\ 10^{44}$ erg/s

If capturing Stellar Winds of the bright young stars:

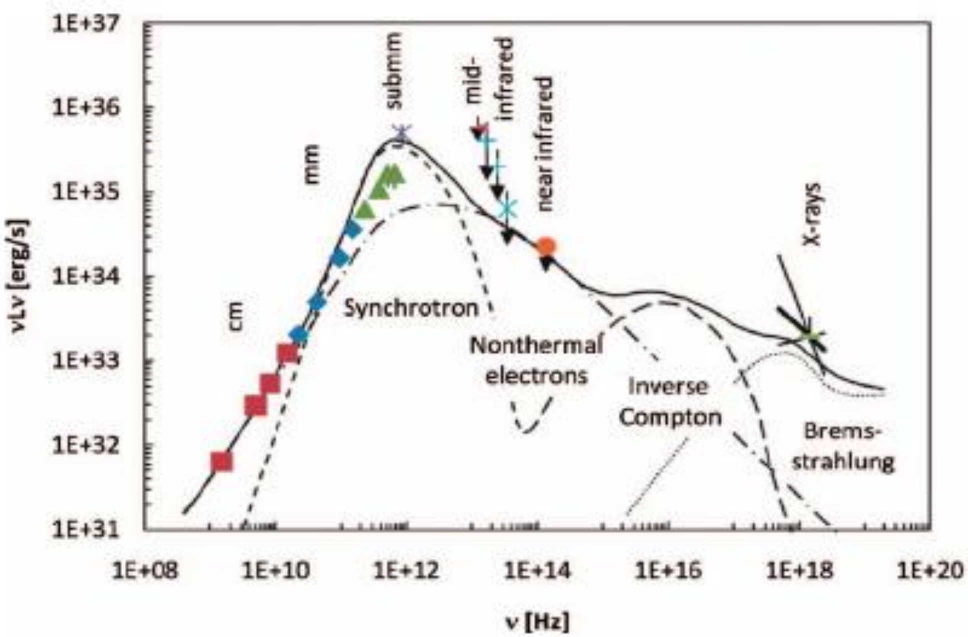
$R_B \sim 10^{17}$ cm = $10^5\ R_S$

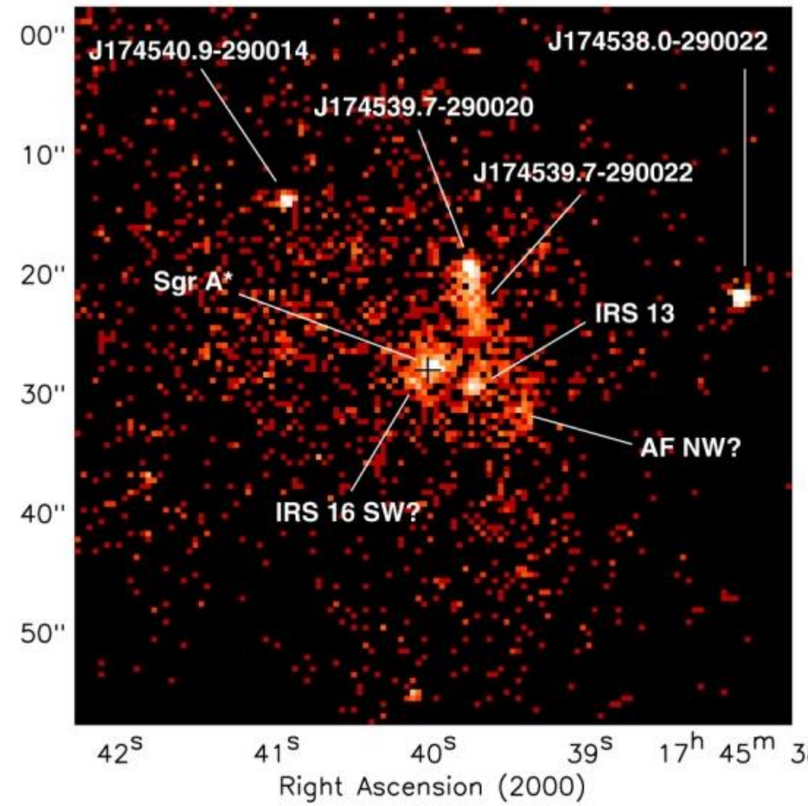
$\dot{M}_{acc} \approx 10^{-3}\ M_\odot\ yr^{-1}$

$L_{acc} = 10^{43}$ erg / s !!!

Sgr A* quiescent emission: a very low luminosity SMBH

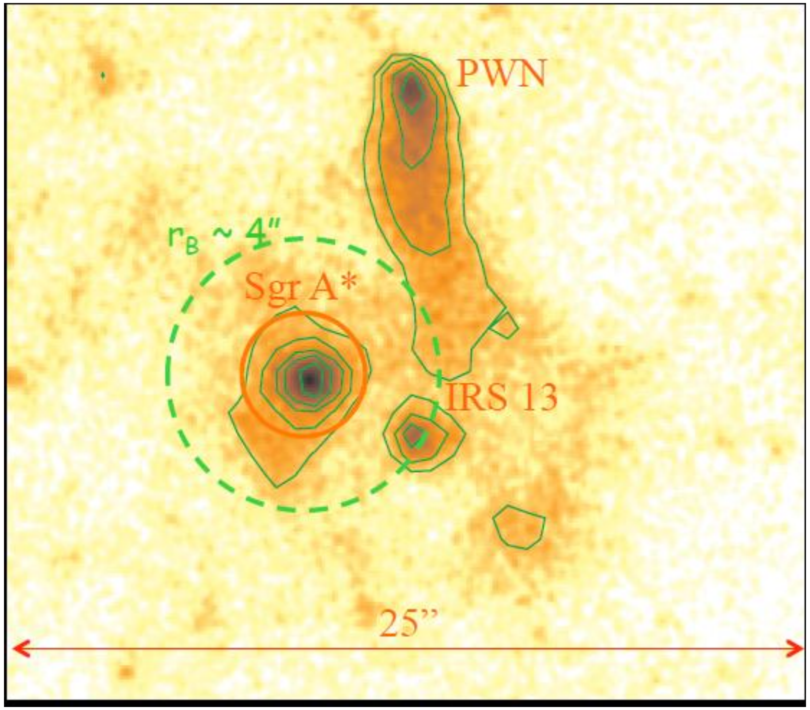
- Sgr A*: the compact, variable, non-thermal radio source associated with the 4 10^6 $M_\odot$ BH of the GC revealed by the proper motion of central cluster stars
- Visible in radio, sub-mm, IR (Flares), X-rays: total luminosity ~ 10^{36} erg/s << L_E
- Very low mass accretion rate, sub-mm polarization => 10^{-8} $M_\odot$/yr << simulated stellar winds $\dot{M}$ ~ $10^{-5/-6}$ $M_\odot$/yr

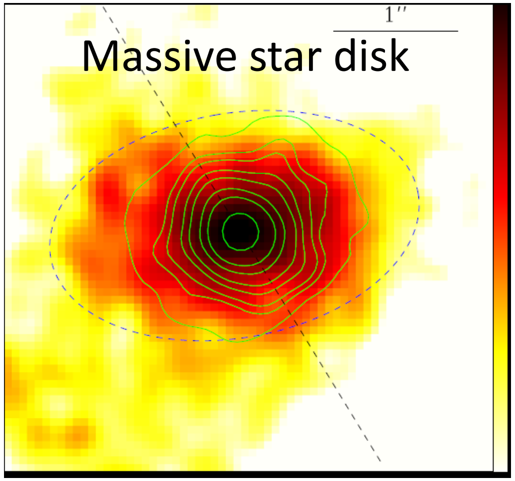


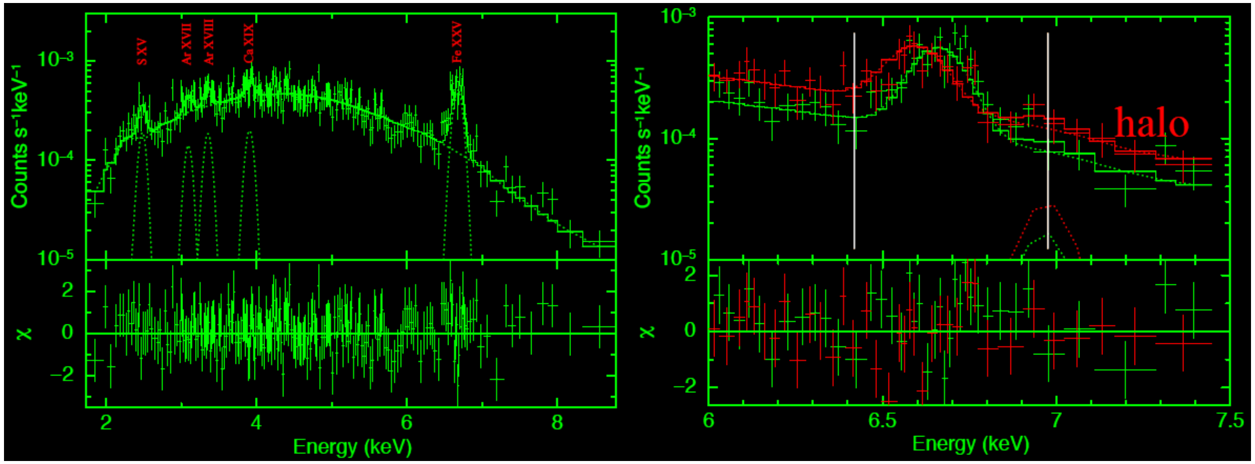


Radiative inefficient accretion flows with outflows / winds. (see Yuan Narayan 2014)

Sgr A* Quiescent emission with 3 Ms Chandra XVP on Sgr A* with ACIS-S



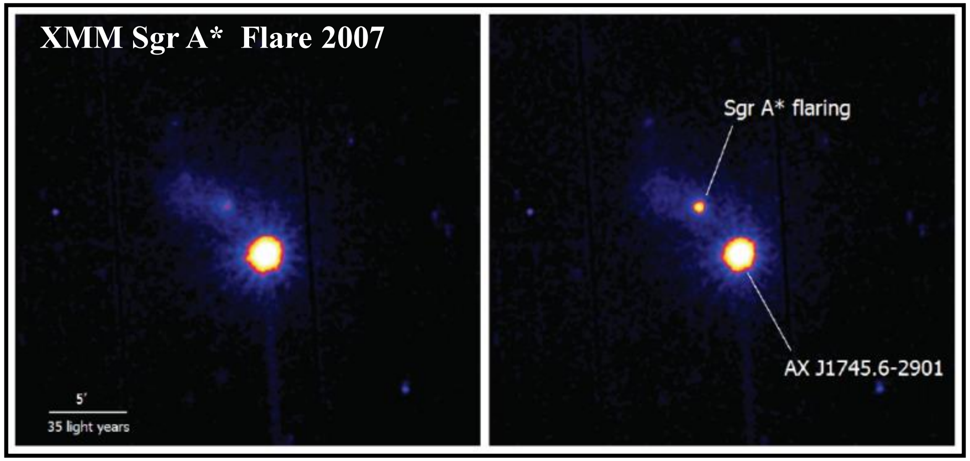


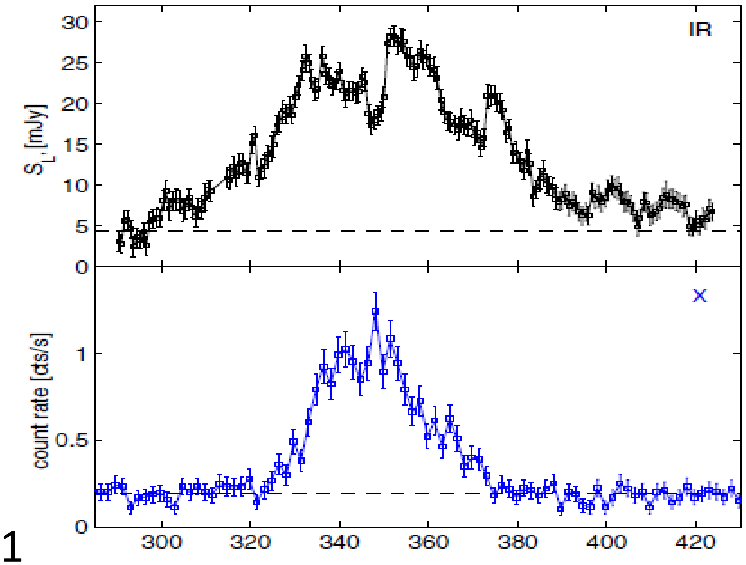


- Quiescent emission morph. ~ star disk
- Lines from the hot accretion flow
- Fe I K not detected => excludes * coronal emission (Sazonov+12)
- Spectrum favors accr. flow + outflows/winds

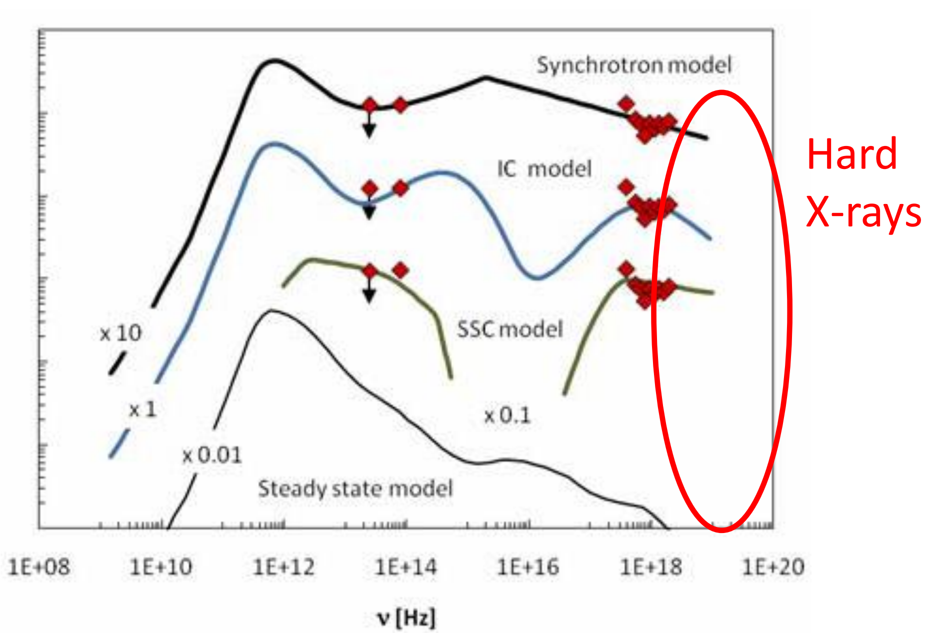
(Wang et al 2013a, 13b)

X and NIR Sgr A* Flaring activity





Doods-Eden et al 09, Porquet et al 08, Trap et al 10, 11



Frequency: ~ 1 / d, NIR: 4/d

Durations: 20 min – 3 hrs

Fastest variations: 200 s => E.R.~ 10 R_s

Max Peak L. ~ 200 times Q.L. = 10^{35} erg/s

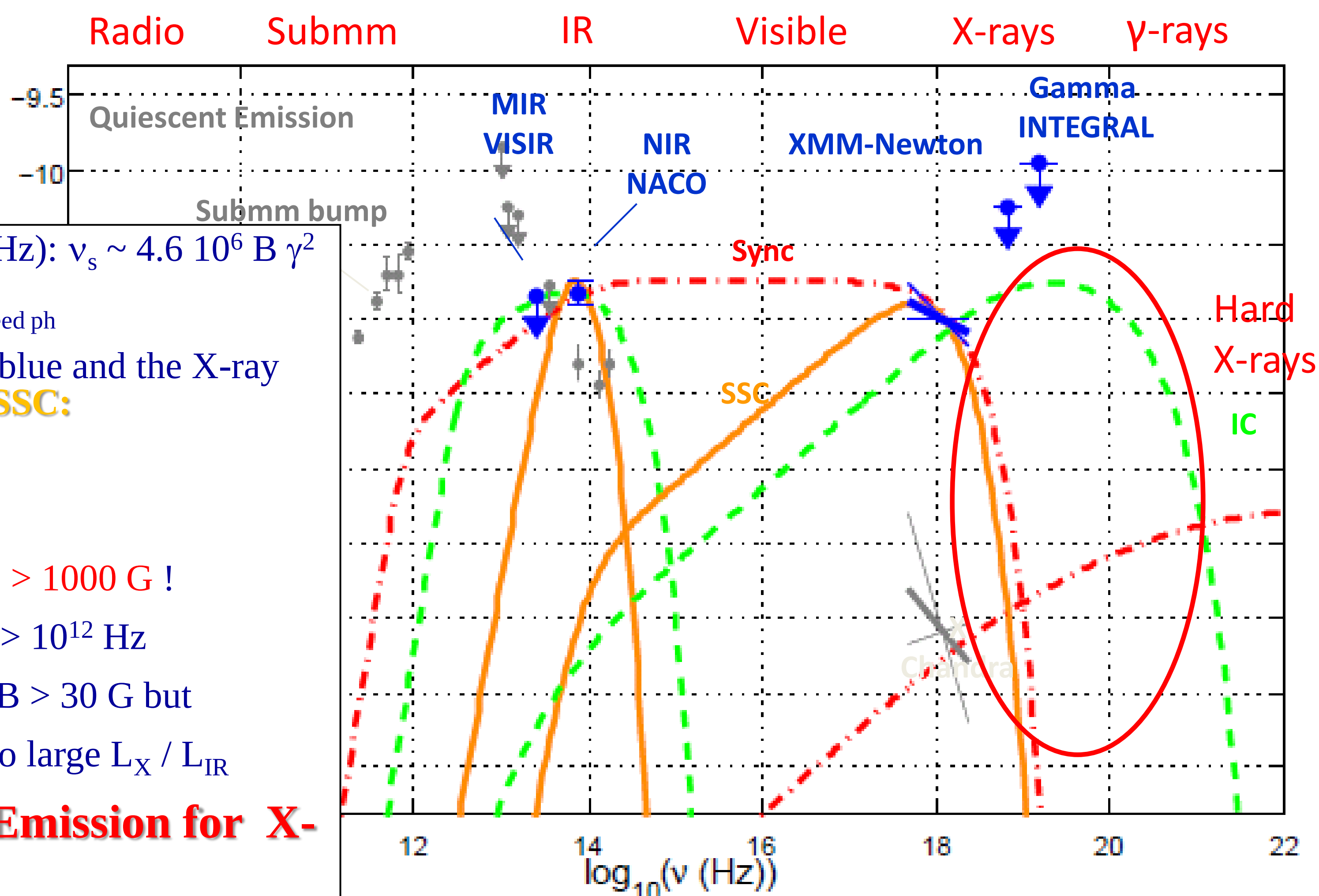
P-L Spectrum (ind. -2.3) no variations

NIR Fl.: Blue/hard spectra, linearly polarized

Claims of modulation/QPO (20 min) no significant and not confirmed

Constraints set by the Sgr A* April 2007 flare

- Infrared flares probably due to Opt-thin Synchrotron emission (GeV e^- in ~ 10 G B)
- X-ray radiation mechanism not clear: Apr 2007 flare suggests Synchrotron



Synchrotron, B (G) ν (Hz): $\nu_s \sim 4.6\ 10^6\ B\ \gamma^2$

Compton : $\nu_{ic} \sim \gamma^2\ \nu_{seed\ ph}$

Since NIR spectrum is blue and the X-ray spectrum soft then for **SSC:**

$\nu_s > 10^{14}$ Hz

$\nu_{ic} < 10^{18}$ Hz

therefore $\gamma < 100 \Rightarrow B > 1000$ G !

For **IC** on sub-mm: $\nu_s > 10^{12}$ Hz

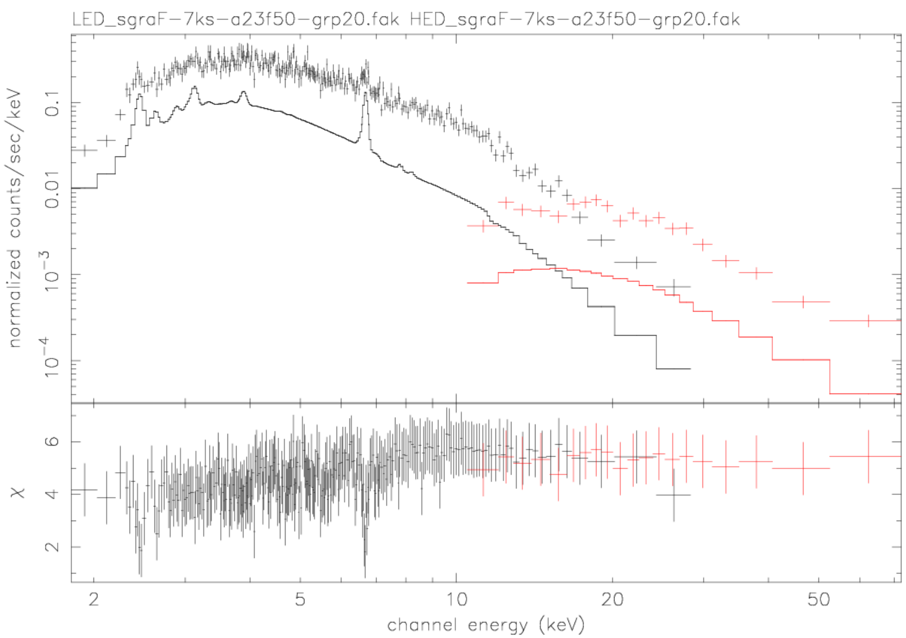
therefore $\gamma < 1000 \Rightarrow B > 30$ G but

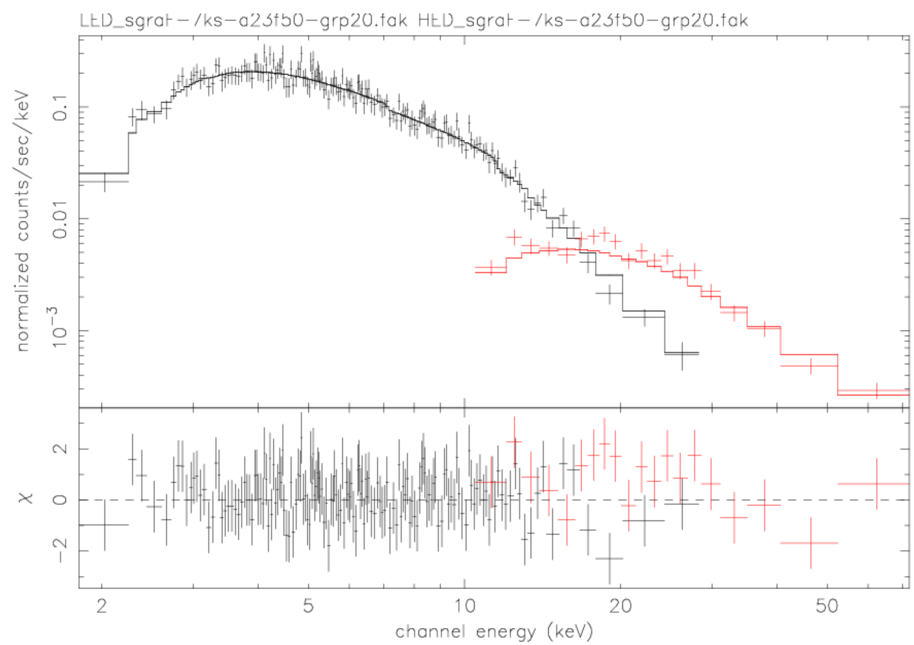
densities too high due to large L_X / L_{IR}

⇒ Synchrotron Emission for X-Rays favored

(Dodds-Eden et al 2009, Trap et al 2010)

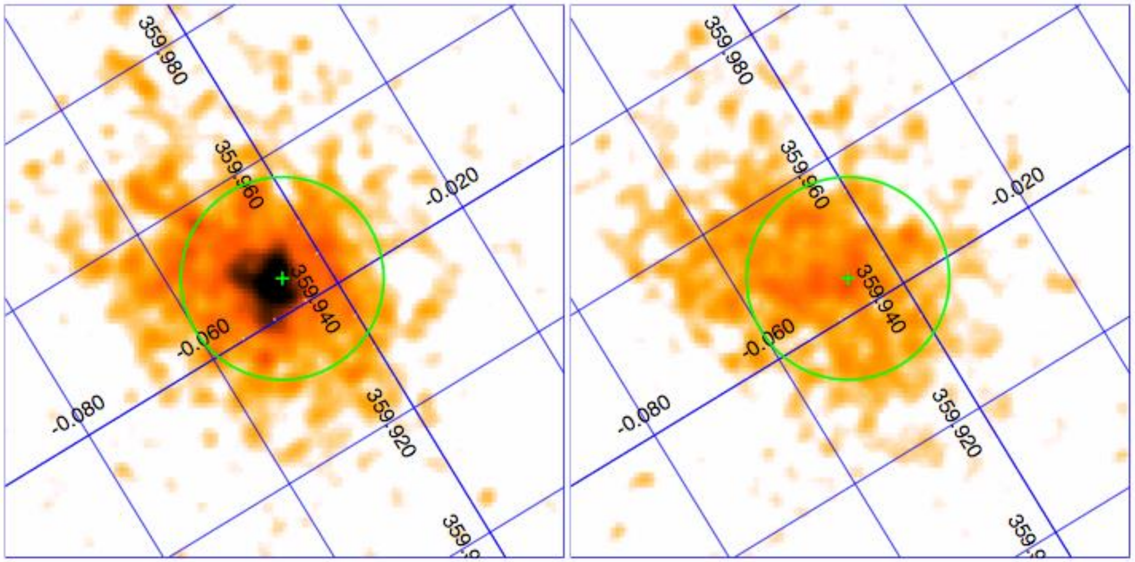
COSPIX simulation of a Sgr A* moderate and soft flare

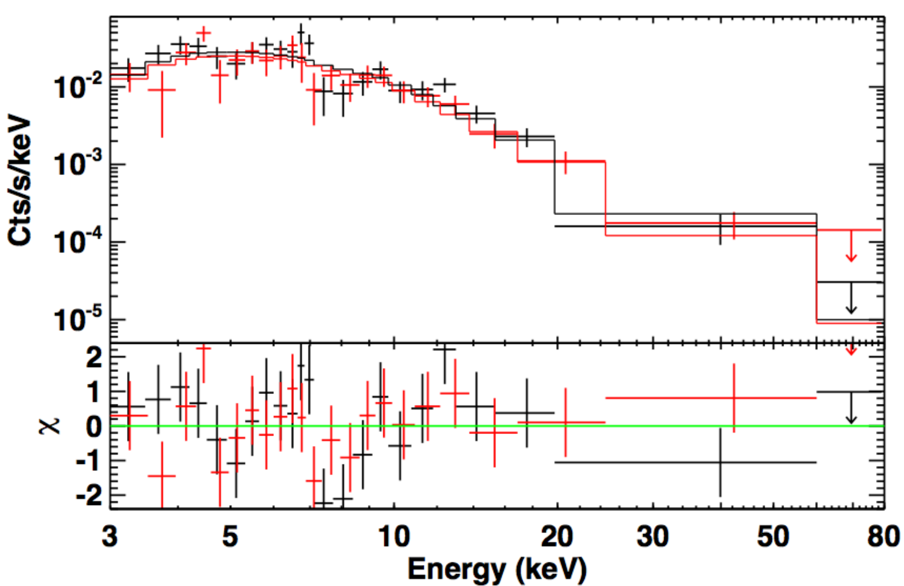




- 50 x Quiescent L. Flare, in 2 hr and soft sp.in. (~ 2.3)
- Detected up to 60 keV, error (90%) on sp. in. ~ 0.04
- Break can be detected => max. energy of electrons
- Search for spectral variability (heating / cooling)
- More sensitive search for QPOs (Goldwurm 2010)

Nu-Star Detection of Sgr A* flares





- 2 flares: July 2012

Oct 2012 (1 with Chandra)

- Spectra up to 40 keV

P-L wt index 2.19 – 1.97

- Fit with EC SSC and SB models

Equivalent chi-squares, SB favored from model parameter

- Indication of Spectral index differences (?)

(Barrière et al 13, 14)

HE Perspectives for the Sgr A* flares

No way to study Quiescent Emission unless Ang. Res ~ few ”

Flares:

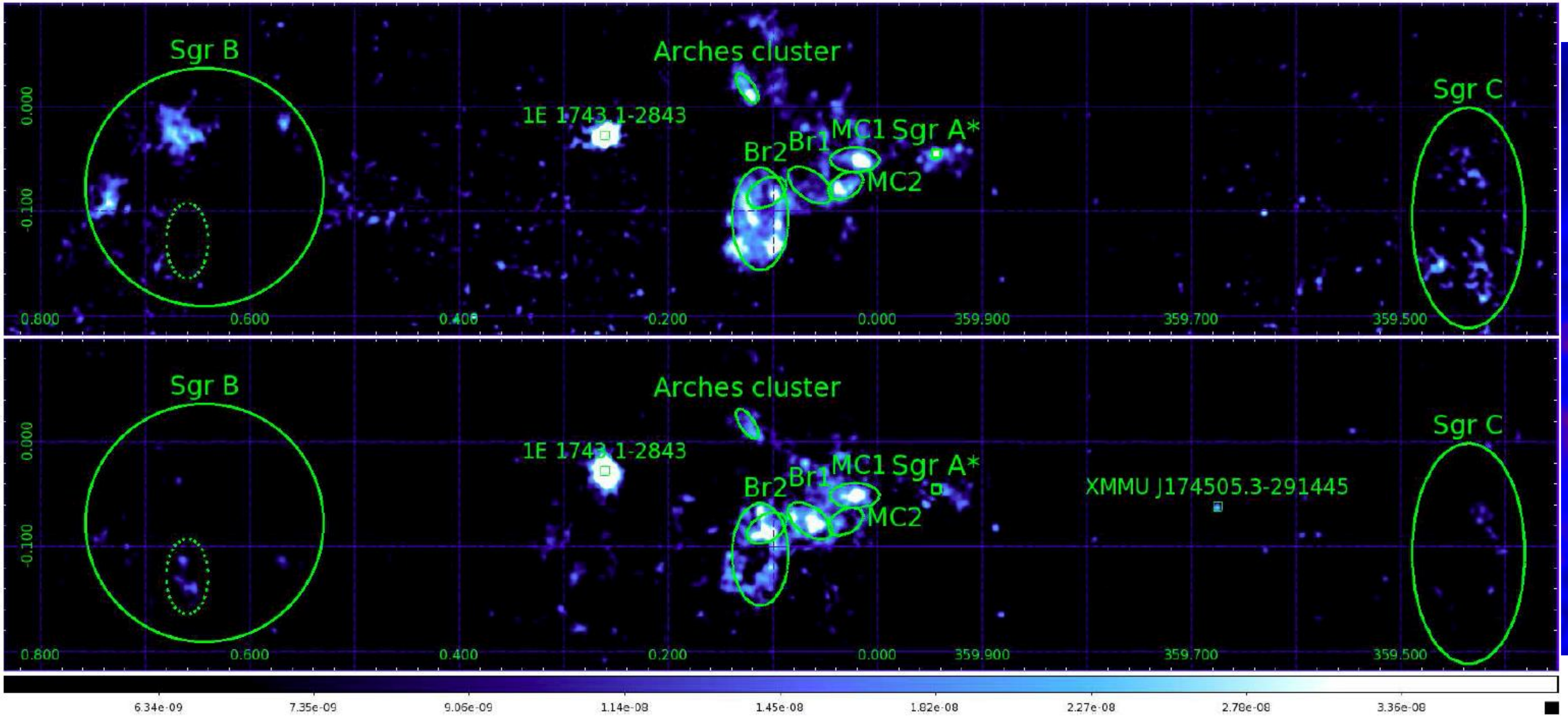
- Search for: spectral variations, modulation/QPOs
- Hard X-ray /soft gamma of Sgr A* flares => Hard tail diagnostics for models
- Polarization would be very useful but source too weak
- Multi lambda obs. for SED evolution and possible delays indicating plasma expansion

However:

- Nu-star: shows pure PL, no break, no clear variations
- Deeper Obs. in H-X to understand heating, cooling not so easy (Astro H: not enough Ang. Res.)
- Crucial are simultaneous obs. in NIR (in 2020 ELT ?)
- More sensitive obs. in X-ray band with Athena+

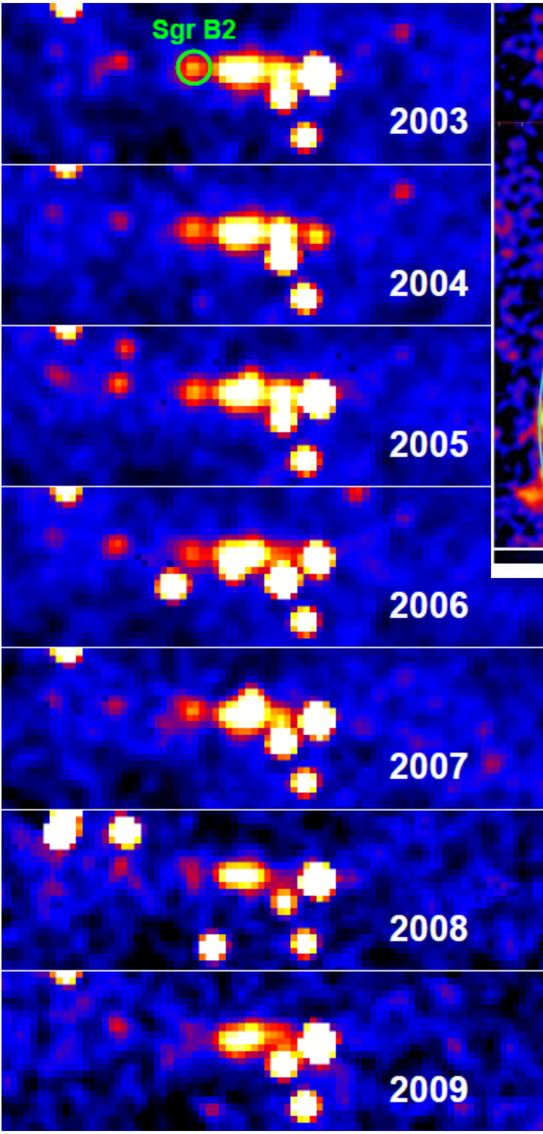
CMZ XMM 2000 – 2012 Surveys

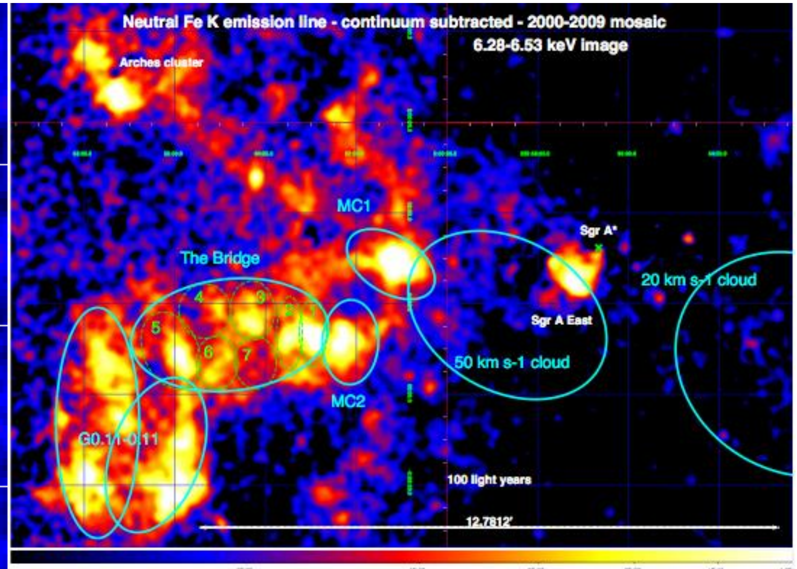
(Soldi et al 2014 in prep)

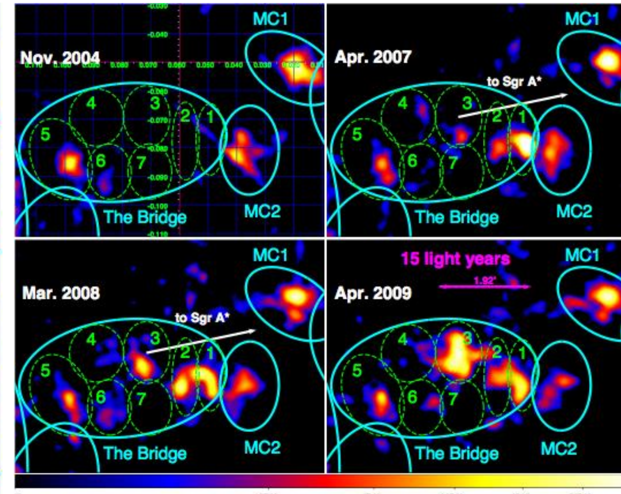


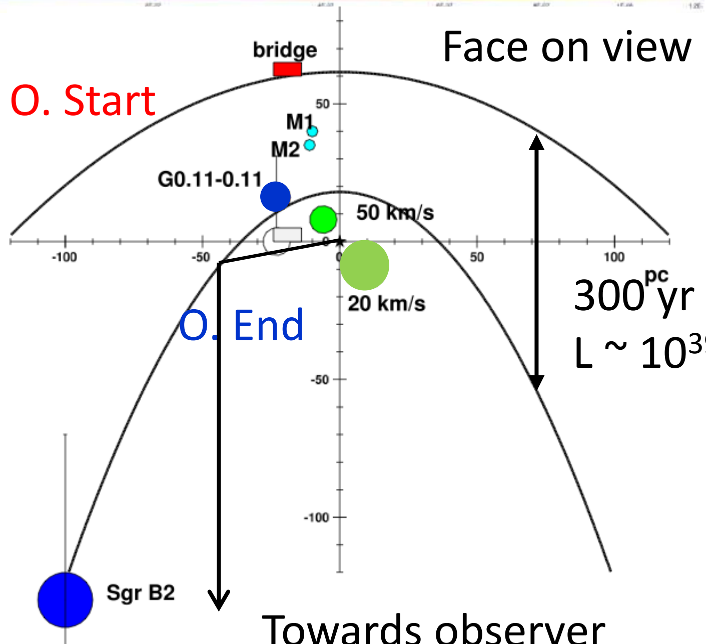
- The Fe k 6.4 keV is correlated to Molecular Clouds and is highly varying
- Interpreted as reflection by neutral material (MC) of hard X-ray emission
- Illuminating source very powerful (10^{39} erg/s) and now off: Sgr A* in the past
- Hard source since line associated to hard continuum up to 200 keV

Variable 6.4 keV line and hard X-rays from GC MC: an echo of Sgr A* intense past activity









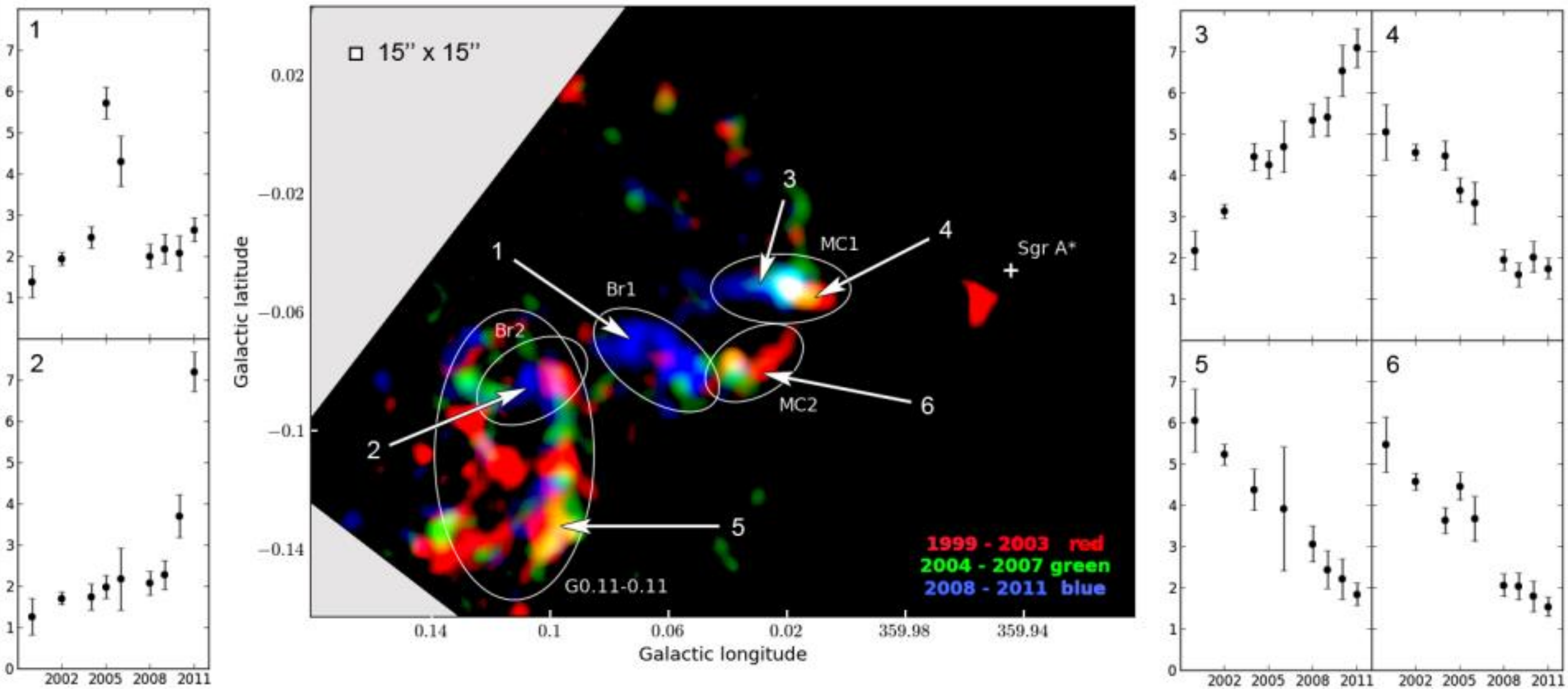
300 yr Outburst
L ~ 10^{39} erg/s

Model:
Sgr A* Outburst started 400 yr back and ended 100 yr ago

Terrier et al 2010
Ponti et al 2010

Bridge increases => Start
Sgr B2 G011 decrease => End
MC1 MC2 const. => Middle
20mk/s 50km/s No flux => Past

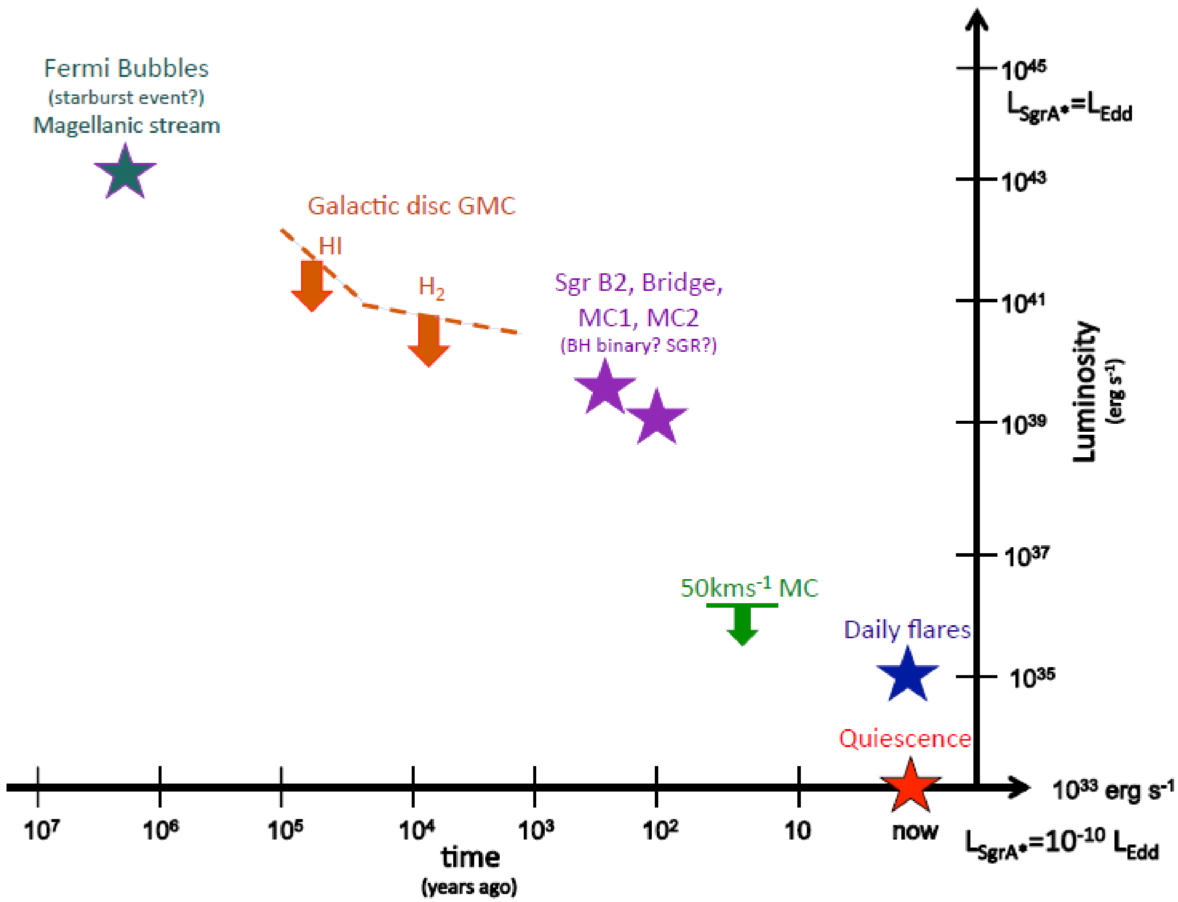
Chandra 1999-2011 GC Survey: 6.4 Fe K and 4-8 keV continuum variations



- Small scale variations show more complex view than derived from XMM
- The Event propagating in the Bridge is short (< 2 yr event)
- Another event with slower increase/decrease timescale in MC1 MC2 (~ 10 yrs)

(Clavel et al 2013)

Reconstructing the activity of Sgr A* over the last 10 Myr



- Including the event that may have generated the Fermi Bubbles ….

(Ponti et al 2014)

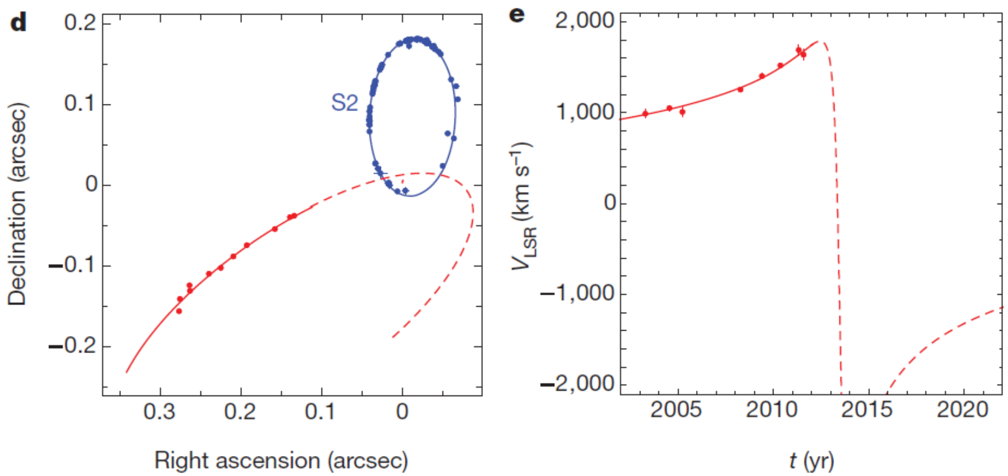
HE Perspectives for the reflection emission in GC

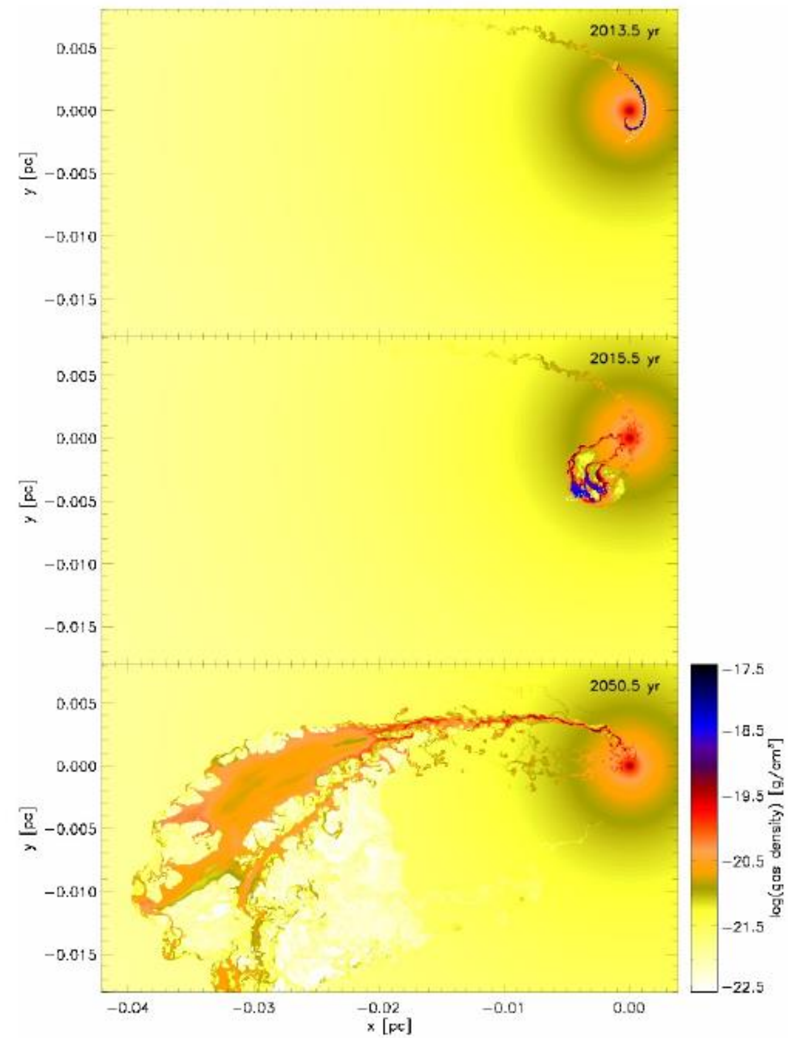
- Monitoring by XMM Chandra Nu-Star Astro H in the next years: tentative reconstruction of Sgr A* light curve in the past 1000 yr
- The general trend is a decrease, it is possible that in 10 yr time most of the emission be very weak, but …

- A very sensitive X-ray instrument like Athena+ WFI is needed => very deep obs. constraints on the past Sgr A* Luminosity down to 10^{37} erg/s over 1000 yr
- Microcalorimeters => detailed neutral Fe (and other elements) line diagnostics => Cloud dynamics, geometry => constraints on Sgr A* luminosity

- Polarization measurements of the hard continuum could be a new important diagnostic because dependent on the incidence angle => provide position along the line of sight of the Molecular Cloud

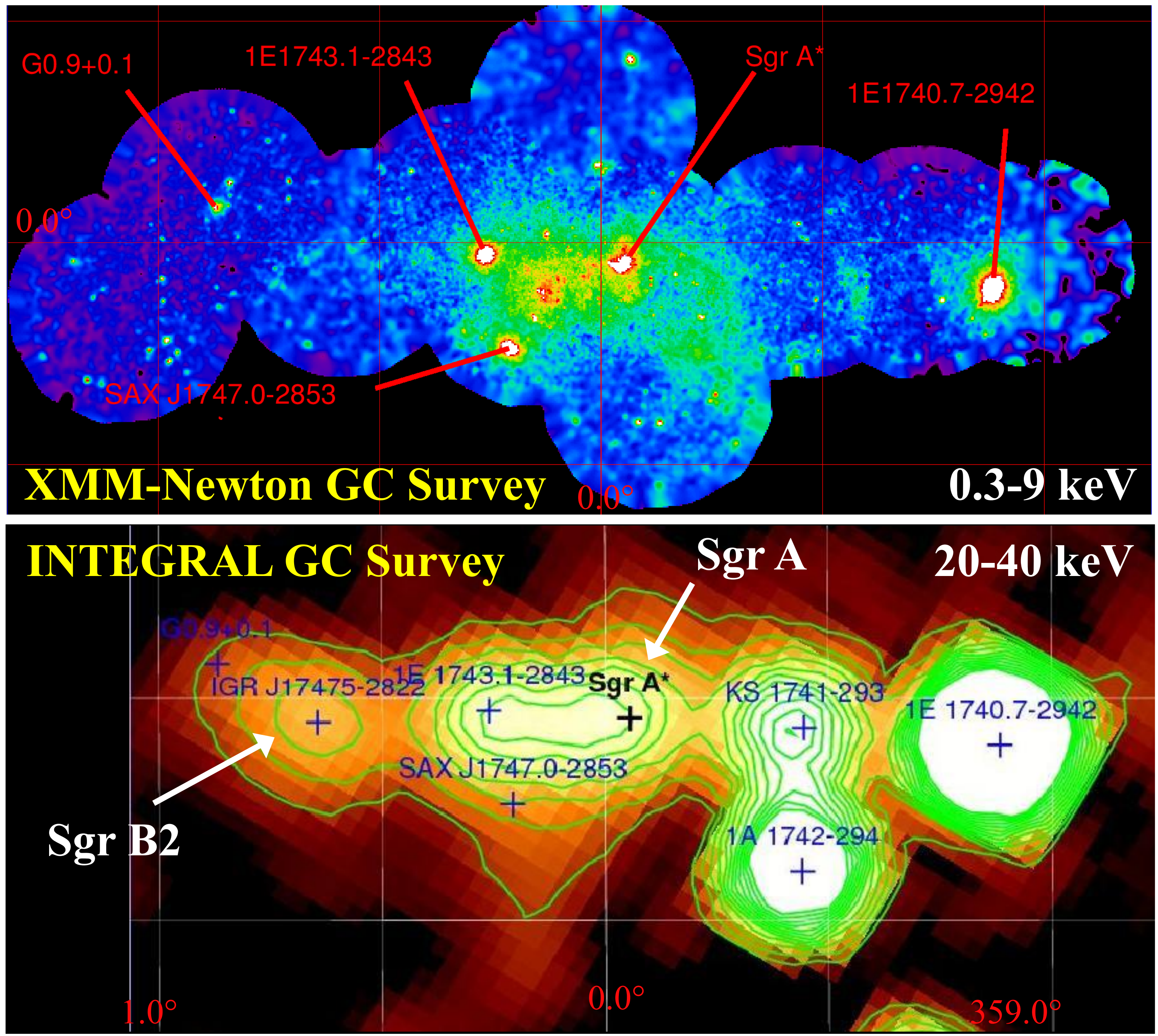
Sgr A* Future activity : G2 object





- VLT discovery of a cold object moving at V ~ 1700 km/s towards Sgr A*
- 3 M_{Earth} gas cloud already being disrupted
- Periastron expected in 2014
- Expected increase in Sgr A* X-ray of 10 x by the G2 Shock with accretion flow may be also flare rate

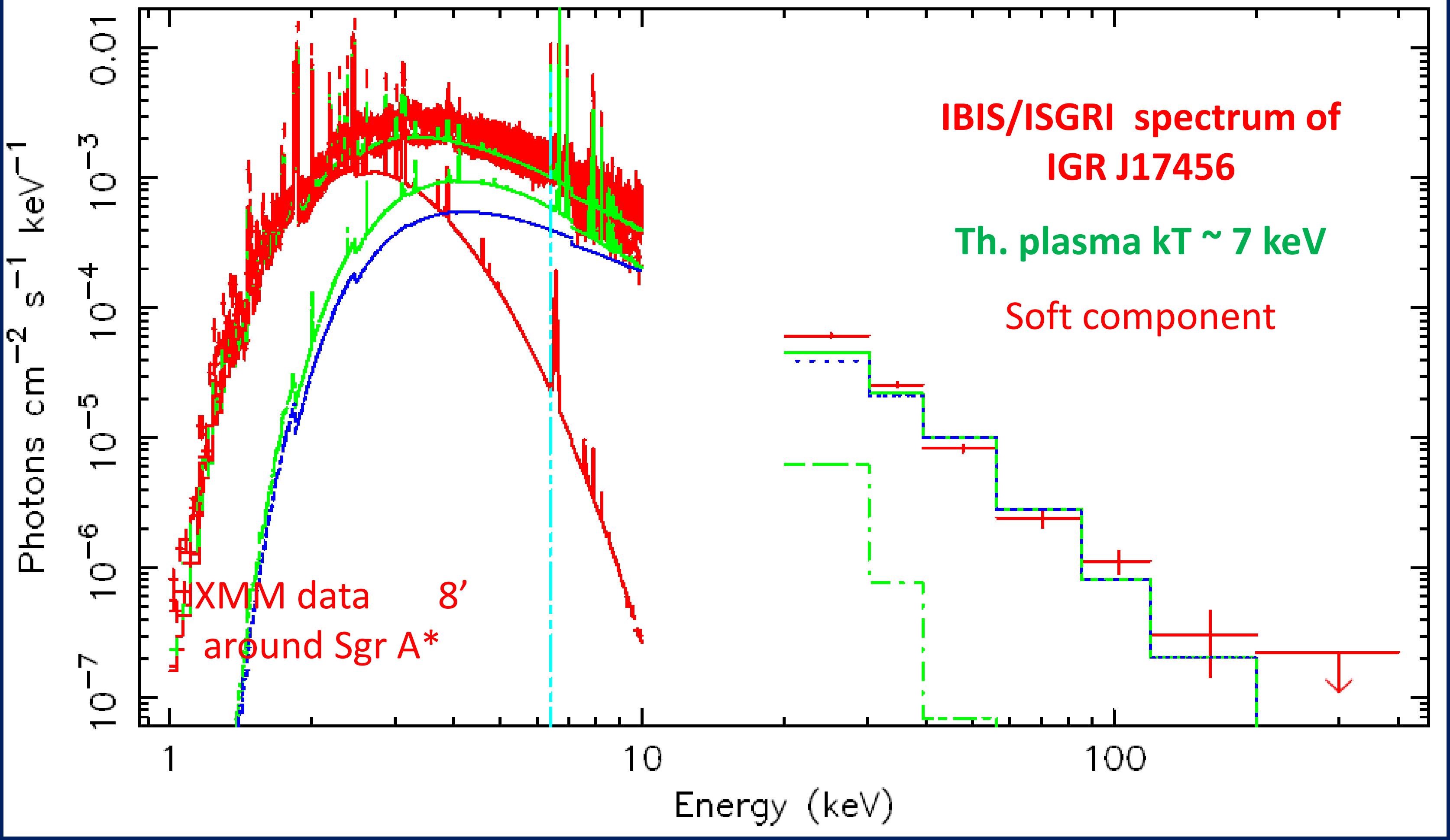
- The accretion rate may increase over a long period: future instruments may be able to see changes in Sgr A* accretion regime



(Decourchelle et al. 2003)

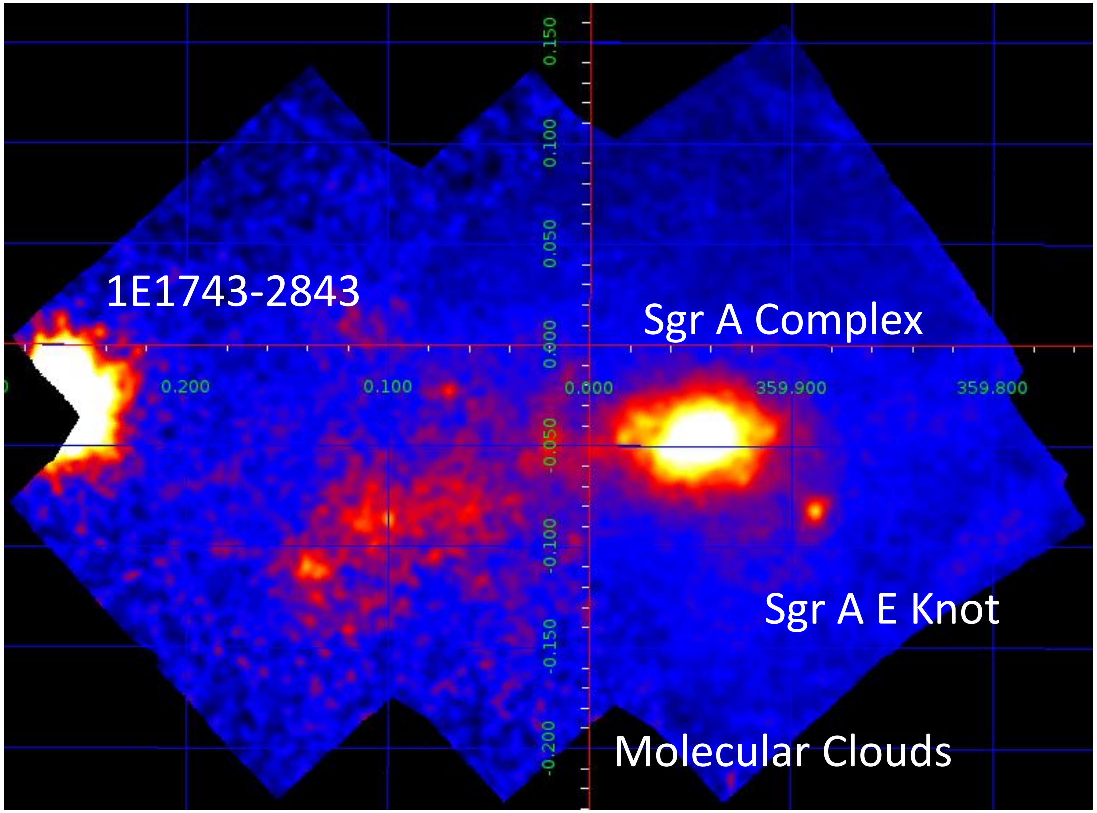
(Belanger et al. 2006)

IBIS/IGRI Spectrum of the IGR C. source

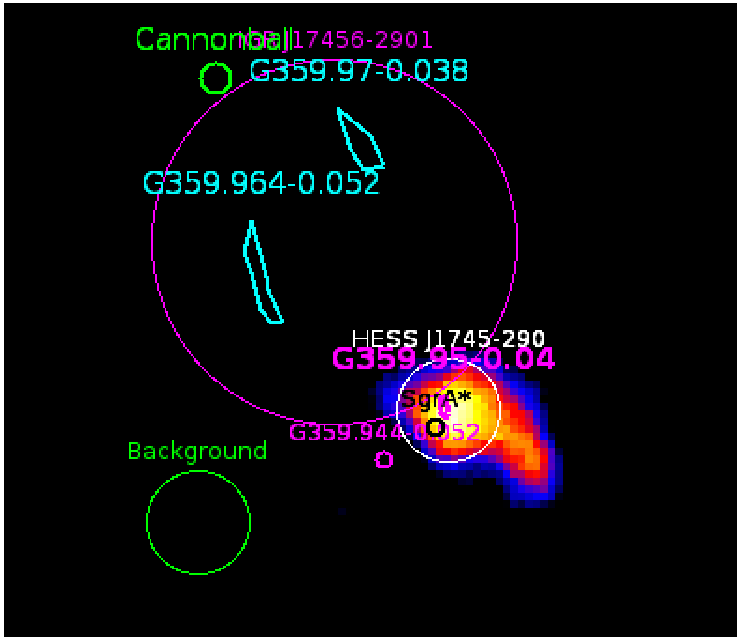


- IGR spectrum: PL (α ~ 3, **L(20-120 keV) ~ 5 10^{35} erg/s)**
- No XMM P-S counterpart, IBIS-PSF-integrated XMM spectrum match IGR
- IGR not explained by extrapolation of the hot thermal plasma model

Nu-Star GC mini-Survey



10-40 keV



- 700 ks Obs., 0.7 pc resolution FWHM at GC
- 1E 1743, Molecular Clouds, Sgr A Complex, Sgr A-E Non-Thermal knot
- Sgr A Complex: PWN Cannon Ball, N-T filaments G359.97-0.038, G359.964-0.052, Thermal-Emission from Sgr A East,
- Strong emission compatible with the PWN G359.95-0.04 => IGR J17456 (and the HESS source ?)
- Also detection of pervasive hard X-ray diffuse emission > 20 keV: no CV's, no GRXE, no Integral emission, not the Suzaku diffuse H-X emission … (Hailey et al. 2014 in prep., Santa Fe talk)

HE Perspectives for the hard diffuse components

- Counterpart of the IGR source: Nu-star will probably resolve the issue
- The new diffuse component found by Nu-star ? Need to see what it is.
- Other Non-thermal features (PWN, Filaments, etc) certainly interesting
- H-X Constraints important to interpret the HESS TeV central source and the diffuse TeV emission => Synergies with CTA project

However:

- Nu-star and Astro H will provide soon a lot of new results needed to draw perspectives of future missions

Summary

Main objectives:

- Sgr A* flares (accretion process in SMBH): spectral variations, hard tail, modulation
- Reflection features (past behavior of Sgr A*): simultaneous line – continuum study, polarization measurements
- Hard Non-thermal features: particle acceleration and interactions in GC (understand GeV/TeV emission)
- Other topics: hot plasma component (hot gas vs. CV population), search for 511 keV line sources

Hard X-ray instrument:

- Spectral-Imaging capabilities
- Large spectral band (Soft-Hard X-rays from 1 keV to 100 keV)
- Polarization capabilities